A Design of a Impedance Tuner With Programmable Characteristic for RF Amplifiers

Seungho Jeong, *Student Member, IEEE*, Junhyung Jeong, *Student Member, IEEE*, and Yongchae Jeong, *Senior Member, IEEE*

***Abstract*—This letter presents the quantitative analysis of a novel reflection type electronic impedance tuner. The proposed impedance tuner consists of a 3-dB 90° coupler, variable phase shifter, and attenuator. A 180° variable phase shifter with constant insertion loss and wide variation range low phase shifting attenuator was used to independently control the magnitude and phase of the proposed impedance tuner. Due to independent controls of phase and magnitude, the proposed impedance tuner has a programmable characteristic. The fabricated impedance tuner shows a uniform impedance distribution in polar form with magnitude deviation of less than average 0.24 dB for standing wave ratio ≤8 at 2.14 GHz.**

***Index Terms*—Attenuator, impedance tuner, load-pull measurements, phase shifter, radio frequency (RF) amplifier.**

I. Introduction

IN THE advanced modern wireless communication, the impedance tuner is one of the key instruments for finding optimal matching impedance of microwave/radio frequency (RF) circuits such as a RF amplifier. It is important to find the optimal impedance because RF amplifiers are operated with specific input–output matching impedances for high efficiency, linearity, output power and so forth. Therefore, to find the optimal matching impedance of RF amplifiers, the impedance tuner can obtain a high level of accuracy, high-level standing wave ratio (SWR) range, high-power handling, and regular impedance distribution.

Among impedance tuners, mechanical tuners offer good performance [1], [2]. However, mechanical tuners have the disadvantages of bulky size, high cost, slow operating speed, and difficulty of fabrication. Recently, to overcome these disadvantages of mechanical tuners, an electronic impedance tuner that uses additional loaded lines was designed [3]. Although the impedance turner presented in [3] can achieve reasonable price and high speed, it is difficult to tune the impedance precisely, and obtain a high level of constant SWR due to mismatching of the reflection coefficient of the loaded line. The SWR range can be enhanced by loading more lines and switches, but this increases the cost and size, and thus the complexity of this tuner.

Other impedance tuners that employ loaded-line and/or stub-based structures have not covered a phase shifting range of over 360° with high-level SWR [4], [5]. Additionally, since the impedance distribution of these tuners is random, it is difficult to precisely find the desired impedance.

Manuscript received September 18, 2016; revised December 28, 2016; accepted February 22, 2017. Date of publication April 24, 2017; date of current version May 8, 2017. This work was supported by "Research Base Construction Fund Support Program" funded by Chonbuk National University in 2016. *(Corresponding author: Yongchae Jeong.)*

The authors are with the Division of Electronic and Information Engineering, IT Convergence Research Center, Chonbuk National University, Jeonju 54896, South Korea (e-mail: ycjeong@jbnu.ac.kr).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LMWC.2017.2691058

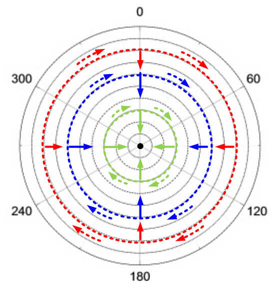


Fig. 1. Impedance distribution of the PIT.

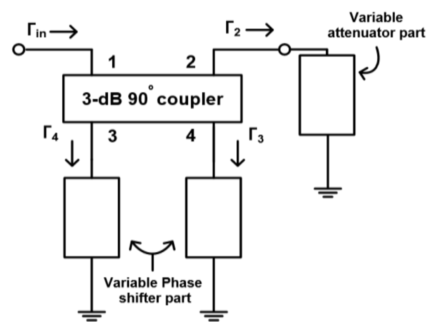


Fig. 2. Block diagram of the proposed PIT.

Recently in 3G/4G communications, the maximum intensional SWR test is performed less than 8 in order to qualify stable operation for RF amplifiers [6]. For satisfying stable SWR, the impedance tuner has to provide larger SWR range than at least 8.

In this letter, a novel design of impedance tuner using a port reduction method is presented. The proposed impedance tuner can provide high-level SWR and programmable characteristic as shown in Fig. 1. Additionally, the proposed impedance tuner is easy to design and fabricate based on analytical design equations.

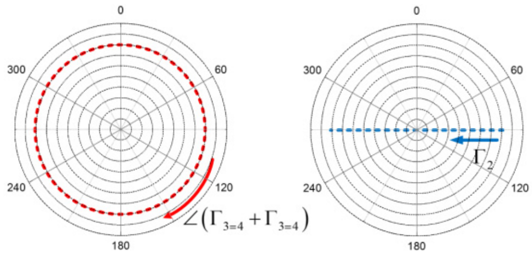
II. Circuit Design

A. Basic Concept of the Proposed Impedance Tuner

Fig. 2 shows a basic block diagram of the proposed programmable impedance tuner (PIT). This circuit consists of a 3-dB 90° coupler, variable phase shifter, and attenuator.

In order to explain the circuit operation, the proposed PIT can be analyzed using the port reduction method [7]. The ideal S-parameters of a 3-dB 90° coupler is defined as

$$S_{3\text{-dB}} = -\frac{1}{\sqrt{2}}\begin{bmatrix} 0 & 0 & -1 & j \\ 0 & 0 & j & -1 \\ -1 & j & 0 & 0 \\ j & -1 & 0 & 0 \end{bmatrix}. \tag{1}$$



(a) (b)

Fig. 3. Γ_{in} variation under the condition of $\Gamma_3 = \Gamma_4$ by varying: (a) phases of Γ_3 and Γ_4 and (b) magnitude of Γ_2.

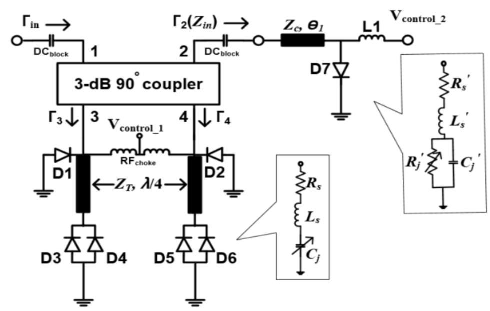


Fig. 4. Detailed schematic of the proposed PIT.

An input reflection coefficient (Γ_{in} or $[S]_{\text{tuner}}$) of the proposed PIT can be obtained from the 4-port S-parameters of the 90° 3-dB coupler and reflection coefficients (Γ_i, $i = 2$, 3, 4) by using the port reduction method as follows:

$$[S]_{\text{tuner}} = S'_{11} + S'_{12}\left[\left(U - S_L S'_{22}\right)\right]^{-1} S_L S'_{21} \tag{2}$$

where

$$S'_{11} = [S_{11}] \quad S'_{12} = [S_{12} \quad S_{13} \quad S_{14}] \quad S'_{21} = \begin{bmatrix} S_{21} \\ S_{31} \\ S_{41} \end{bmatrix} \tag{3a}$$

$$S'_{22} = \begin{bmatrix} S_{22} & S_{23} & S_{24} \\ S_{32} & S_{33} & S_{34} \\ S_{42} & S_{43} & S_{44} \end{bmatrix} S_L = \begin{bmatrix} \Gamma_2 & 0 & 0 \\ 0 & \Gamma_3 & 0 \\ 0 & 0 & \Gamma_4 \end{bmatrix}. \tag{3b}$$

For simplification, assume that the reflection coefficient at port 3 is identical to the reflection coefficient at port 4 ($\Gamma_3 = \Gamma_4$). Then $[S]_{\text{tuner}}$ can be simplified as

$$[S]_{\text{tuner}} = \Gamma_{\text{in}} = -\Gamma_2\Gamma_3\Gamma_4 = -\Gamma_2\Gamma_3^2 \approx |\Gamma_2|\angle(2\Gamma_3). \tag{4}$$

In this equation, Γ_3 and Γ_4 are the reflection coefficients of the phase shifters, and Γ_2 is the reflection coefficient of the attenuator. Equation (4) shows that $[S]_{\text{tuner}}$ depends on the reflection coefficients of the phase shifter and attenuator. To achieve uniform impedance distribution with high SWR in the proposed PIT, Γ_3, and Γ_4 should have a 180° phase shifting range with constant magnitude, whereas Γ_2 should have a wide attenuation variation range with low phase deviation. Fig. 3 shows $[S]_{\text{tuner}}$ variations according to the phase of Γ_3 and magnitude of Γ_2. However, the practical $[S]_{\text{tuner}}$ cannot cover the entire SWR range because the p-i-n diode in the attenuator cannot have infinite resistance and the varactor diode of phase shifter has some loss.

Fig. 4 shows a detailed schematic of the proposed PIT, which connects phase shifting loads at ports 3 and 4, and the attenuation load at port 2. In additional $D1$–$D6$ are varactor diodes whereas $D7$ is p-i-n diode.

The phase shifter consists of a parallel connection of varactor diodes and $\lambda/4$ transmission line (TL) terminated with parallel varactor diodes. In this strcture, the varactor diodes are connected in parallel to get a 180° phase shift as well as to enhance linearity by compensating parasitic components. The reflection coefficient of the phase shifter is obtained as (5) using the equivalent circuit model of the varactor diodes

$$\Gamma_3 = \frac{\left(2Z_T^2 R_s - 2Z_0 Z_T^2 - Z_0 R_s^2 + \omega_0^2 Z_0 L_s^2 + \frac{Z_0}{\omega_0^2 C_j^2} - \frac{2Z_0 L_s}{C_j}\right) + j\left(2Z_T^2 \omega_0 L_s - \frac{2Z_T^2}{\omega_0 C_j} - 2\omega_0 Z_0 R_s L_s + \frac{2Z_0 R_s}{\omega_0 C_j}\right)}{\left(2Z_T^2 R_s + 2Z_0 Z_T^2 + Z_0 R_s^2 - \omega_0^2 Z_0 L_s^2 - \frac{Z_0}{\omega_0^2 C_j^2} + \frac{2Z_0 L_s}{C_j}\right) + j\left(2Z_T^2 \omega_0 L_s - \frac{2Z_T^2}{\omega_0 C_j} + 2\omega_0 Z_0 R_s L_s - \frac{2Z_0 R_s}{\omega_0 C_j}\right)} \tag{5}$$

where Z_T and Z_0 are characteristic impedances of the $\lambda/4$ line and port reference impedance. Similarly, L_s, R_s, and C_j are circuit parameters of the equivalent varactor diode model.

To obtain constant magnitude with large phase variation, the parasitic components of varactor diodes must be compensated by properly choosing the characteristic impedance of the $\lambda/4$ line. In this letter, circuit parameters of the equivalent varactor diode model are obtained by the Deloach method as $L_s = 2.2$ nH, $R_s = 1.45$ Ω, and $C_j = 0.7$–4 pF. Therefore, from (5), the constant phase shifter is obtained with $Z_T = 61.7$ Ω.

Additionally, the low phase deviation attenuator consists of TL terminated by p-i-n diode and can be analyzed by finding the input impedance Z_{in} as described in [8]

$$Z_{\text{in}} = Z_c A \frac{(Z_c + B\tan\theta) - (B - Z_c\tan\theta)\tan\theta}{(Z_c + B\tan\theta)^2 + (A\tan\theta)^2} - j\frac{(Z_c + B\tan\theta)(B - Z_c\tan\theta) + A^2\tan\theta}{(Z_c + B\tan\theta)^2 + (A\tan\theta)^2} \tag{6}$$

where

$$A = R'_s + \frac{R'_j}{1 + (\omega R'_j C'_j)^2}, \quad B = \frac{\omega C'_j R'^2_j}{1 + (\omega R'_j C'_j)^2} - \omega L'_s. \tag{7}$$

In order to obtain pure resistive variation of Γ_2, Z_{in} must cross the $Z_0 + j0$ Ω point in the range of signal attenuation, so that no p-i-n phase deviation of the attenuator can be obtained. To minimize the phase deviation, the parasitic components of diode should be compensated by properly choosing the characteristic impedance Z_c and electrical length θ. The circuit parameters of the p-i-n diode are given as $L'_s = 1$ nH, $R'_s = 3$ Ω, and $C'_j = 0.35$ pF. From (6), the values of Z_c and θ are determined as 87.8 Ω and 177° for junction resistance variation of 50∼ infinite, respectively, which can provide a high-level of SWR with small power consumption.

III. Fabrication and Measurement Results

A. Fabrication

For experimental verification of the proposed PIT, the PIT was designed and fabricated for an operating frequency range of 2.09–2.19 GHz with center frequency 2.14 GHz. Rogers Corporation RT/Duroid 5880 substrate with a dielectric constant (ε_r) of 2.2 and a thickness (h) of 31 mil was used.

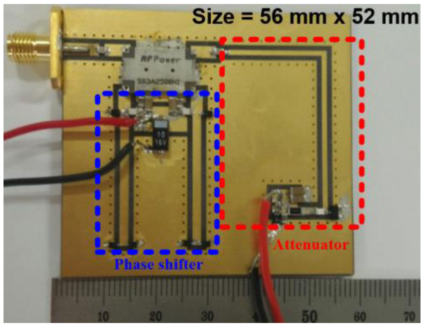


Fig. 5. Photograph of the proposed PIT.

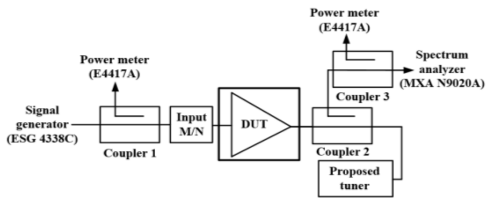


Fig. 6. Impedance tuner setup for load-pull measurement.

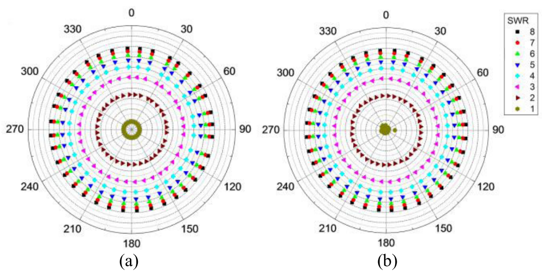


Fig. 7. Impedance distributions according to SWR at 2.14 GHz at input power of 5 dBm: (a) simulation and (b) measurement results.

Fig. 5 shows a photograph of the proposed PIT. The PIT was fabricated by using S03A2500N1 90° hybrid coupler, SMV 1233-011LF varactor diodes, and HSMP-4810 p-i-n diode. The characteristic impedance and electrical length of TL for the phase shifter are 61.7 Ω and 89.8°. Similarly, to achieve low phase deviation of the attenuator, the characteristic impedance and electrical length of TL are 82.4 Ω and 185°, respectively.

B. Measurement Result

Fig. 6 shows the impedance tuner setup for load-pull measurement. Fig. 7 plots the simulated and measured impedance distributions, and these results show that the proposed PIT with coupler 2 provides uniform impedance distribution with small magnitude and phase deviations. In this experiment, the bias voltages of varactor diode and p-i-n diode are tuned independently. In order to cover all points for SWR from 1 to 8, the varactor diode bias voltage is varied from 0 to 15 V whereas p-i-n diode bias voltage is varied from 0 to 1.4 V. From measurements, the proposed impedance tuner covers SWR 1–8 with magnitude and phase maximal deviations of less than 0.39 dB and 1.1° at 2.14 GHz, respectively. In addition, the proposed PIT provides that the magnitude and phase deviations for SWR 1–8 are small in the frequency range of 2.09–2.19 GHz. The maximal magnitude variation of the proposed PIT is 0.35 dB when SWR = 8 at 2.09 GHz. Therefore, the fabricated PIT provides almost flat SWR up to 8.

TABLE I
IMPEDANCE TUNERS COMPARISON

	Mechanical Tuner [1]	Electronic tuners		
		[3]	[4]	This work
Frequency (GHz)	0.4 ~ 4	0.82 ~ 0.92	0.85	2.09 ~ 2.19
SWR	≤ 15	2.5 and 6	≤ 4	≤ 8
Cost	High	Low	Low	Low
Impedance distribution	Program-mable	Program-mable	Random	Program-mable
Tunability	Continuous	Discrete	Continuous	Continuous
Size (mm^2)	376 × 228	100 × 50	None	56 × 52
Power capability	54 dBm	None	None	16.38 dBm
IIP3	None	None	30 dBm	26 dBm

Additionally, the proposed impedance tuner also shows linearity (IMD3 < -30 dBc) up to an average power of 13 dBm. Also, the proposed PIT has maximal deviations of less than 0.29 dB and 6.5° up to 13 dBm using the setup in Fig. 6. The linearity and power handling capability of the PIT can be further improved by connecting more varactor diodes in parallel, or high-power varactor.

The performance comparison the proposed PIT with the state of the arts is summarized in Table I. In comparison with electronic tuners, the proposed PIT shows the highest SWR, compact size and continuous characteristic.

IV. CONCLUSION

In this letter, the PIT was designed employing the phase shifter and the attenuator on a 90° 3-dB coupler. The proposed tuner independently controls bias voltage of the phase shifter (0–15 V) and attenuator (0–1.4 V). The fabricated impedance tuner provides the SWR ≤8 with uniform impedance distribution at 2.14 GHz. Also, the proposed impedance tuner shows power capability of 16.4 dBm and IIP3 of 26 dBm. The proposed PIT shows excellent performances in the frequency range 2.09–2.19 GHz. In addition, the proposed impedance tuner is compact in size, and easy to design and fabricate. The proposed impedance tuner is expected to apply an important role for characterizing RF amplifiers and other circuits in wireless communications systems.

REFERENCES

[1] *MT981BL10 High-Power Automatic Tuners*, Maury Microw., Ontario, CA, USA.
[2] A. Curutchet *et al.*, "Early demonstration of a high VSWR microwave coaxial programmable impedance tuner with coaxial slugs," in *Proc. Eur. Microw. Conf.*, Sep. 2015, pp. 642–645.
[3] Y. Bae, U. Kim, and J. Kim, "A programmable impedance tuner with finite SWRs for load-pull measurement of handset power amplifiers," *IEEE Microw. Wireless Compon. Lett.*, vol. 25, no. 4, pp. 268–270, Apr. 2015.
[4] M. Schmidt, E. Lourandakis, A. Leidl, S. Seitz, and R. Weigel, "A comparison of tunable ferroelectric Π- and T-matching networks," in *Proc. 37th Eur. Microw. Conf.*, Oct. 2007, pp. 98–101.
[5] J.-S. Fu, X. A. Zhu, J. D. Phillips, and A. Mortazawi, "A ferroelectric-based impedance tuner for adaptive matching applications," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2008, pp. 955–958.
[6] *SKY65387-11:2110-2170 MHz Variable Gain Amplifier*, Skyworks, Woburn, MA, USA.
[7] H.-R. Ahn, *Asymmetric Passive Components in Microwave Integrated Circuits*. Hoboken, NJ, USA: Wiley, Sep. 2006.
[8] Y. Kim, S. Shim, T. Moon, G. Chaudhary, and Y. Jeong, "Mathematical analysis of novel low phase deviation variable attenuator," in *Proc. IEEE Asia–Pacific Microw. Conf.*, Dec. 2010, pp. 1743–1746.